

# FU Orionis: A Binary Star?

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## Abstract

By using the ALFA adaptive optics system at the 3.6m telescope of the Calar Alto Observatory we detected a faint red star in the apparent vicinity of FU Ori, the prototype of the FUor outburst stars. Independent confirmation of the detection is obtained from archival PUEO/CFHT images. The separation between the companion candidate and FU Ori is 0."50 and their brightness contrast is around 4 magnitudes. We discuss the possible nature of the newly detected star based on near-infrared photometry and its proper motion relative to FU Ori. The photometric data are consistent with a nearby late-type main sequence star, a background giant star, and a pre-main sequence star. On the basis of the proper motion and the stellar surface density in the direction towards FU Ori, we argue that the probabilities of the first two options are very low.

*Subject headings:* binaries: general — stars: individual (FU Ori) — stars: pre-main-sequence — techniques: high angular resolution

## 1 Introduction

Recent studies of low-mass stars in the star-forming regions Taurus (Gullbring et al., 1998) and Orion (Robberto et al., 2003) indicate surprisingly low accretion rates between  $\dot{M} \simeq 10^{-7} - 10^{-10} M_{\odot} \text{yr}^{-1}$ . These accretion rates are far too low to build up solar-type stars on timescales of the order of  $10^6$  yr, as it is

expected in the current picture of low-mass star formation (see Lada 1999 and references therein). An elegant alternative to the quiescent, steady accretion can be the occurrence of periodic, short events of intense accretion ( $\dot{M} \simeq 10^{-4} M_{\odot} \text{yr}^{-1}$ ), during which a significant fraction of the disk mass can be accreted (Hartmann & Kenyon, 1996). The well-known FUor objects (Herbig, 1966, 1977) may represent this intense accretion phase of otherwise quiescent T Tauri stars (Hartmann & Kenyon, 1996). Thus, if FUor outbursts are typical to *all* T Tauri stars, these outbursts might be the dominant way of mass accretion.

Models based on the enhanced accretion rates are in general successful in explaining the observed properties of the FUor outbursts (Hartmann & Kenyon, 1985; Kenyon, Hartmann, & Hewett, 1988), but the causes of the onset of the rapid accretion are still disputed. Suggested possibilities include thermal instabilities in the disk (see, e.g., Lin & Papaloizou 1985; Kawazoe & Mineshige 1993; Bell & Lin 1994) and perturbations from close companions (Bonnell & Bastien, 1992; Clarke & Syer, 1996), but up to now none of these explanations could be confirmed observationally.

However, earlier high-angular resolution observations led to the detection of companions for the FUor objects L1551 IRS 5 (Rodríguez et al., 1998) and Z CMa (Koresko et al., 1991), with a separation of 45 and 93 AU respectively. Moreover, Kenyon, Hartmann, & Gomez (1993) found RNO 1B and 1C to be a FUor binary. Infrared long-baseline interferometry shows that FU Ori might have a close companion with a separation as small as  $0.35 \pm 0.05$  AU, although these observations could be explained more naturally with the presence of a circumstellar disk (Malbet et al., 1998).

In this letter we present adaptive optics imaging of the young pre-main sequence star FU Ori and the detection of a faint red star in its apparent vicinity. Further results from our imaging campaign to search for companions of young stars were reported by Apai et al. (2003).

In order to avoid confusion, throughout the letter we use the name FU Ori for the prototype star ( $\alpha = 05^h 45^m 22.^s 6$ ,  $\delta = +09^\circ 04' 12''$ ), while the term FUor stands for the class of stars named after FU Ori.

## 2 Observations and data reduction

On 2002 October 27 we observed FU Ori and the star HD 38224 as PSF-reference using the near-infrared camera Omega Cass mounted at the 3.6m

telescope at the Calar Alto Observatory, Spain. The plate scale used in our observations was  $0.''038 \text{ pixel}^{-1}$ . The weather conditions changed between good and excellent, with mean optical seeing of  $0.''7$ . The observations aimed to enhance the contrast of the imaging system by the subtraction of a reference PSF from the target object. In order to compensate for the temporal variations of the PSF due to the changes in the atmosphere and in the optical system, we applied short observing *cycles*, alternating between the target and the PSF reference star.

Each *cycle* consisted of four dithering positions around the target with roughly 83 seconds ( $98 \times 0.842 \text{ second}$ ) spent at each position. Thus, the total on-source integration time of a cycle was 332 seconds, both in J and Ks filters. In the J filter we carried out two cycles on FU Ori, two cycles on the PSF star and two additional cycles on FU Ori. These cycles were observed immediately one after the other to minimize the PSF variations. Due to the approach of sunrise, in Ks band we did only one cycle on FU Ori, one on the PSF star and one again on FU Ori. The resulting total integration times were 1320 s in J and 660 s in Ks on FU Ori, and 660 s in J and 330 s in Ks on the PSF star.

The basic data reduction was conducted in the standard fashion with flat field correction and bad pixel removal. The sky frame for each cycle was obtained by taking the minimum of the images at different dithering positions. This sky frame was subtracted from each individual image of a given *cycle*. Following this, the frames from a single *cycle* were combined into a mosaic image. The relative shifts of the individual frames were determined by cross-correlating the images.

In order to enhance the contrast between a possible companion and FU Ori, we subtracted a brightness-scaled and positionally aligned PSF, known from the PSF reference star (for details of the method see Pantin et al. 2000).

### 3 Results

Our data reduction procedure yielded the PSF-subtracted J and Ks band images of the star FU Ori (see Fig. 1). The central part ( $r < 0.''4$ ) is heavily contaminated by the PSF-subtraction residuals and speckle phenomena. The residuals originate from the imperfect PSF subtraction due to the temporal variations of the PSF. The speckle pattern differences lead to the *speckle boiling* (Racine et al., 1999), resulting in a dotted noisy pattern. South-east from

the FU Ori residuals an over-subtracted (negative) star is visible. This faint star is a previously unknown (visual) companion of the PSF-reference star HD 38224. This (visual) companion star is also identifiable on the reduced (non-PSF-subtracted) images of HD 38224, but it becomes very evident after the subtraction. We note that in the Ks band the first Airy-ring of this star is well visible.

The major result of our observations is the detection of a previously unknown star in the FU Ori images to the south of FU Ori (see Fig. 1). In the following we will refer to this star as FU Ori S. The following facts exclude the possibility of FU Ori S being an artifact:

1. The star has been detected in both the J and Ks bands at the same location (see panels A and B in Fig. 1): The position difference is less than  $0.''01$  and the position angle difference is only  $2.^{\circ}8$  – within the errors of the position determination ( $0.''03$ ;  $3^{\circ}$ ).
2. The star shows an Airy-ring pattern in the Ks band image, like the (visual) companion of the PSF reference star.
3. The star is also detected at the same position, when another PSF star (HD 201731 in the J-band, XY Cep in the Ks band) from the same night is used as PSF reference. Although these PSF-stars were observed several hours before FU Ori, subtracting them from FU Ori reveals again the existence of FU Ori S.
4. Archival data from the AO system PUEO mounted on the Canada-France-Hawaii Telescope (shown in Fig. 2) provides independent confirmation for the existence of FU Ori S. The co-added image was obtained through the K continuum filter ( $\lambda_c = 2.260\mu m$ ,  $\Delta\lambda = 0.060\mu m$ ) with a total exposure time of 11.2 seconds.

With respect to FU Ori, we derive from our ALFA images a position angle of  $160.^{\circ}8 \pm 3^{\circ}$  and a separation of  $0.''50 \pm 0.''03$  (linear separation =  $225 \pm 14$  AU) for FU Ori S. The positional error given here is dominated by the centering uncertainties of FU Ori S (around 0.5 pixels).

Accurate photometry of FU Ori S suffers from the PSF-subtraction residuals and the speckle noise. In order to reduce these effects, we used a photometric aperture as small as  $0.''19$  ( $\simeq 1.6 \times \text{FWHM}$ ). Our photometric conversion factors were deduced by applying this aperture to the stars FU Ori, HD 38224, and HD 201731 and using their 2MASS Point Source Catalogue fluxes. The error on the conversion factor in the J band is estimated to be 0.22 mag. In Ks band, due to the saturation of FU Ori and HD 201731 we can only derive the conversion factor for HD 38224. As the AO system per-

forms better in the Ks band than in the J band, the conversion factor error in the Ks band should be smaller than that in the J band. To be conservative we adopt the error of the conversion factor in the Ks band to be the same as that in the J band. Another major uncertainty of the aperture photometry of FU Ori S comes from the speckle pattern. To estimate its influence on our photometry, we have integrated the flux of speckle noise in 18 positions over an aperture with the same diameter as used for FU Ori S. Comparing these fluxes to that of FU Ori S, we estimate an error due to speckle noise of 0.11 mag and 0.08 mag in J and Ks bands, respectively.

Based on the aperture photometry and the described error estimates, we derive an apparent brightness of  $J = 10.65 \pm 0.25$  mag and  $Ks = 9.64 \pm 0.23$  mag for FU Ori S. The apparent brightness of FU Ori is  $J = 6.519 \pm 0.023$  mag,  $K = 5.159 \pm 0.020$  mag (Cutri et al., 2003). Therefore, the brightness contrast between FU Ori and FU Ori S amounts to 4.13 and 4.48 mag in the J and Ks bands, respectively.

## 4 Discussions

The result of our AO observations is the identification of a faint star close to FU Ori, the prototype of the FUor stars. In the following we assume 450 pc as the distance of FU Ori. Our photometry shows the unusually red color of FU Ori S ( $J - Ks = 1.01 \pm 0.34$ ) which is similar to that of FU Ori itself ( $J - K = 1.36 \pm 0.03$ ). Although unambiguously determining the nature of FU Ori S from only two near-infrared fluxes is not possible, valuable conclusions can be drawn from its photometric properties. In this section, we first discuss the probability of FU Ori S being an unrelated field star, then the possibility of FU Ori S being a late-type main sequence (MS) star, a giant/supergiant or a pre-MS star with Ks-band infrared excess.

The very vicinity of FU Ori S to FU Ori suggests that FU Ori S is most probably a companion of FU Ori. The 2MASS Point Source Catalogue (Cutri et al., 2003) shows that the FU Ori region is not densely populated: in a region with a radius of  $8'$  centered on FU Ori there are only 6 stars brighter than FU Ori S ( $Ks = 9.64$  mag) in the K band. In analogy to earlier binarity surveys, we would consider any bright star closer than  $\sim 2.''5$  to FU Ori as a companion. Therefore, the probability for a bright field star to be considered as a companion by chance is less than  $\frac{6}{(8 \times 60)^2 \pi} \times 2.5^2 \pi = 1.6 \times 10^{-4}$ . This estimate strongly supports the view that FU Ori S is a companion of FU Ori.

The photometry and the proper motion data give further constraints on the nature of FU Ori S. If it is a MS star, its spectral type – assuming no extinction – will be later than K4 to match its red color. A simple comparison of the absolute brightness of MS stars to the apparent brightness of FU Ori S sets the upper distance limits of 120 pc for K4 and 50 pc for M6 spectral types. Such a nearby star, however, is likely to display a measurable proper motion over the 5 years time base between the ALFA and PUEO observations. For example, from the Hipparcos catalogue (Perryman et al., 1997) the average annual proper motion of stars located at distances between 50-120 pc and within a radius of  $10^\circ$  around FU Ori is  $38 \text{ mas yr}^{-1}$ . In contrast, the absolute proper motion of FU Ori itself is less than  $6 \text{ mas yr}^{-1}$  (see Tycho catalogue (Høg, 1997)). Thus, if FU Ori and FU Ori S are unrelated, their relative separation should have changed by an amount of  $0.''19$  over 5 years, a clearly detectable shift in the AO images. Comparing the PUEO position to that derived from ALFA we found a position difference of  $10 \pm 48 \text{ mas}$  (the centering error of the PUEO images is estimated to be 1 pixel). This gives a proper motion limit of  $2 \pm 10 \text{ mas yr}^{-1}$  and indicates that FU Ori S is unlikely to be a nearby MS star.

Such a very small relative proper motion can be consistent with a star co-moving with FU Ori or a distant background object. Considering the option that FU Ori S is a background giant – assuming the case of no extinction for simplicity – we obtain that giants with spectral types between K1 and M7 at distances between 2 to 34 kpc are consistent with the photometry. Additional reddening would decrease the distances but would not change the overall picture.

The third and most exciting possibility is that FU Ori S is a pre-MS star associated to FU Ori itself. A simple comparison to the isochrones of Baraffe et al. (1998) shows that the observed fluxes are in an overall good agreement with the predicted magnitudes of a  $\sim 1.1 M_\odot$  star of the age of  $10^6 \text{ yr}$  at the 450 pc distance of FU Ori ( $J_{\text{BCAH}}=10.61 \text{ mag}$  and  $K_{\text{BCAH}} = 9.80$ , for  $[M/H] = 0$ ,  $Y = 0.275$ , and  $L_{\text{mix}} = H_p$ ). Apparently FU Ori S is somewhat redder than these pre-MS isochrones. This could be due to a reddening of  $A_v = 1.1 \text{ mag}$  and/or the infrared excess arising from warm circumstellar material. We point out, that assuming FU Ori S as a pre-MS star provides a natural explanation for the observed brightness, color and the lack of proper motion relative to FU Ori. Assuming a physical association between FU Ori S and FU Ori, taking the mass of FU Ori S to be  $1.1 M_\odot$  and the mass of FU Ori to be  $0.5 M_\odot$ , the typical mass of T Tauri stars, the

primary in the FU Ori binary system is in fact FU Ori S, rather than FU Ori itself. Moreover, if we assume circular orbits in the plane of sky, the above masses and the linear separation ( $225 \pm 14$  AU) yield an orbital period of  $\sim 2700$  yr.

In the case of FU Ori S being physically associated with FU Ori, the properties of the FU Ori binary matches well with those used in the model of Bonnell & Bastien (1992). For example, in their 1G and 1O simulations the mass ratios are 0.67 and 0.42, respectively, and the intervals between the companion periastron passes are around 2500 and 2100 yr (see Bonnell & Bastien, 1992, Figs 2 and 3). In contrast, the mass ratio and the companion separation of the FU Ori binary candidate differs strongly from those used in the Clarke & Syer (1996) model in which a companion of mass of  $10^{-2} M_{\odot}$  at a very close distance ( $\sim 0.1$  AU) to the primary is exploited to trigger the enhanced accretion. We note that the detection of more and more companions of FUor stars points to the possibility that they may play an active role in triggering the outbursts.

## 5 Conclusions

Our AO-assisted near-infrared imaging led to the detection of a red point source south of the well-known outburst star FU Ori. We discuss the possible nature of this object and conclude that the observed properties are consistent with either a pre-MS star at the distance of FU Ori or – with much smaller probability – a red background giant star. We argue that mid-resolution optical spectroscopy can discriminate between these cases.

As the FUor outbursts may be of central importance for star formation, a possible companion to the prototype object FU Ori can have a major impact on the outburst models. In particular, the close fly-by of the companion could lead to disk perturbations, therefore, providing an external triggering of the outbursts of FUor stars.

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Figure 1: PSF-subtracted images of FU Ori, (a) in J and (b) in Ks band. North is up and the east is to the left. The positions of FU Ori, FU Ori S, and the visual companion of the PSF reference star are indicated with numbers 1-3 in (b). The image scale is marked in (b).

Figure 2: CFHT PUEO image of FU Ori through the K continuum filter ( $\lambda_c = 2.260\mu m$ ,  $\Delta\lambda = 0.060\mu m$ ). The observations were made on 1997 December 22. The total exposure time is 11.2 s and no PSF-subtraction was applied. The position of FU Ori S is indicated.

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